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Quantum Interference Filters Based on Oxide Superconductor Junctions for Microwave Applications

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Abstract—We have studied superconducting quantum interference filters (SQIFs) based on bicrystal neodymium gallate substrates, which can be used in the microwave frequency range. The characteristics of a serial SQIF have been compared for the first time with those of a single superconducting quantum interference device (SQUID) and a chain of serially connected SQUIDs with equal areas of superconducting loops. The regime of SQIF operation with a voltage–flux (V–Φ) characteristic determined by the magnetic-field dependence of the critical current in the Josephson junction has been analyzed. It is shown that the output noise of a SQIF measured with a cooled amplifier in the 1–2 GHz range is determined by the slope of the V–Φ characteristic. The influence of a spread in the parameters of Josephson junctions in the SQIF on the integral V–Φ characteristic of the whole structure is considered.

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In the microwave frequency range, amplifiers based on superconducting quantum interference devices (SQUIDs) are characterized by a noise temperature that is close to the quantum limit hf/k (see, e.g., [1, 2]), where f = 0.3–0.7 GHz is the signal frequency, h is the Planck constant, and k is the Boltzmann constant. Such a high sensitivity of these amplifiers in combination with a superconducting strip antenna is important for the development of a new class of receivers for telecommunication systems. In recent years, the possibility of using ultra-high-sensitivity SQUIDs as readout elements in quantum [3] and axion [4] detectors has also been discussed. On the other hand, SQUIDs are known to possess a low saturation power (and, hence, small dynamic range D), which is related to technical difficulties in providing feedback in the microwave frequency range (such feedback in low-frequency SQUIDs allows a dynamic range of up to D ~ 100 dB to be reached). The saturation power in Josephson devices without feedback is proportional to the characteristic voltage $V_0 = I_C R_N$, where I_C is the critical current and R_N is the normal state resistance. The V_0 value is on the order of 200–300 μV for the Josephson junctions based on low-temperature superconductors. For the junctions based on oxide superconductors, this parameter reaches about 1 mV at liquid nitrogen temperature and attains several millivolts at lower temperatures.

A natural solution to the problem of increasing D is provided by a chain of synchronously operating Josephson junctions [5, 6], in particular, those based on the oxide superconductors. However, the scatter of parameters, which is especially pronounced in such junctions, significantly complicates the realization of such multielement synchronous structures [7]. A series of several (N) noninteracting SQUIDs also provides for an increase in the voltage V (proportional to N), but this system exhibits an uneven voltage–field characteristic $V(B)$ that is also related to the scatter of parameters.

Recently, it was suggested [8–10] to use multielement arrays of SQUIDs with a certain distribution of loops areas, representing quantum interference filters (SQIFs). At a sufficiently large number N of elements in a SQIF, the magnetic-field dependence of the critical current $I_C(B)$ exhibits a large central peak at low fields B, while the side maxima are suppressed as a result of the interference of $I_{ci}(B)$ components of the SQUIDs with various loop areas. As a result, the amplitude of the voltage–field characteristic $V(B)$ of the SQIF increases and the range of linearity (constant slope) of this characteristic expands. However, the features of SQIF application in microwave amplifiers have not been studied until now. Note that the results of dc measurements confirmed the advantages of SQIFs as high-sensitivity zero magnetic field detectors [10].

This Letter presents the first results of microwave measurements, including the output noise, for SQIFs based on bicrystal neodymium gallate $NdGaO_3$ (NGO) substrates. In comparison to the SQIFs on strontium titanate ($SrTiO_3$) substrates used in [8–10], the NGO bicrystals are characterized by much lower permittivity

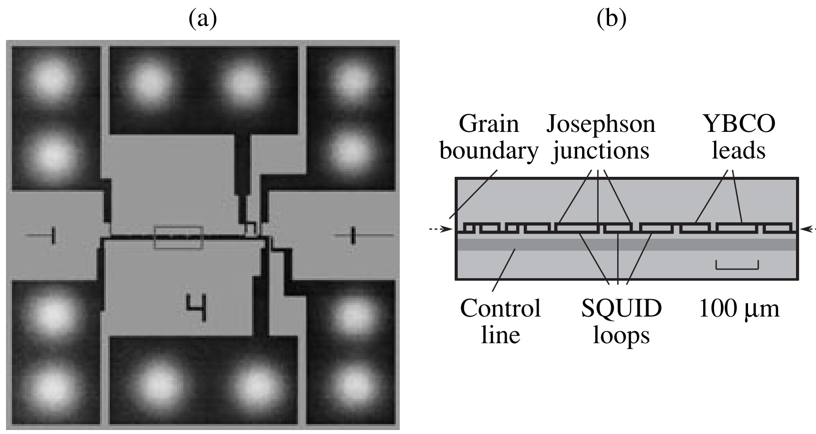

Fig. 1. Schematic diagrams showing (a) the typical topology of a 5 × 5 mm SQIF chip and (b) the central part of a chain of SQUIDs constituting the SQIF.

(ε = 25) and losses in the microwave range. In this study, the characteristics of a serial SQIF have been compared for the first time with those of a single SQUID and a chain of serially connected SQUIDs with equal loop areas.

Figure 1 shows the typical SQIF topology. The corresponding thin-film structure was formed by means of ion-plasma and chemical etching in an $YBa_2Cu_3O_x$ film deposited onto NGO by dc cathode sputtering at a high oxygen pressure. The technology of bicrystal Josephson junctions was described in more detail elsewhere [11]. A single SQUID had a loop area of $S_s = 5 \times 7$ μm^2; a regular chain consisted of 20 serially connected SQUIDs with the same loop area, and a SQIF comprised 20 serially connected SQUIDs with various loop areas in the range 35–700 μm^2. The widths w of Josephson junctions in different chips varied from 5 to 10 μm. The input magnetic flux was determined by the field generated either by an external magnetic coil, or by a dc current passing in a superconducting strip situated near the SQIF array.

We have studied the current–voltage (I–V) characteristics of sample structures at various magnetic fields and microwave signal parameters and measured the dependences of the critical current and the voltage drop (at a fixed current) on the external magnetic field. The output noise of SQIF and SQUID structures was measured using a cooled preamplifier with a noise temperature of $T_{N1} = 8 \pm 2$ K and a gain of $G = 21$ dB in a frequency band of $f = 1$–2 GHz, after which the signal was amplified by a warm amplifier with $T_{N2} = 130$ K and $G = 40$ dB, passed via a quadratic detector, and measured by a dc nanovoltmeter. The output signal was calibrated in equivalent noise power temperature units (T_N) with allowance for the intrinsic noise of the measuring circuit and the impedance mismatch. The spectrum of the amplified signal was monitored by a spectrum analyzer.

Let us compare the $V(B)$ characteristics of the structures of three types: (i) a single SQUID with an asymmetrically set current, (ii) a chain of SQUIDs, and (iii) a SQIF. Figure 2 presents the $V(B)$ curves for a chain of SQUIDs and for the corresponding SQIF. In addition to the small-scale SQUID-type modulation with a period corresponding to the loop area of S_s = 35 μm^2, we have also observed a modulation of the $\sin B/B$ type that is clearly revealed by the experimental $V(B)$ curve for the SQUID chain. In the case of junctions with a width of w = 10 μm, the effective area of magnetic field penetration is $S_{eff} = w^2/4$ [12]. As a result of the field concentration, this value differs by almost an order of magnitude from $S_j = 2w\lambda_L = 3$ μm^2, where λ_L = 0.15 μm is London's magnetic-field penetration depth. As a result, S_s is not much greater than S_{eff}, and

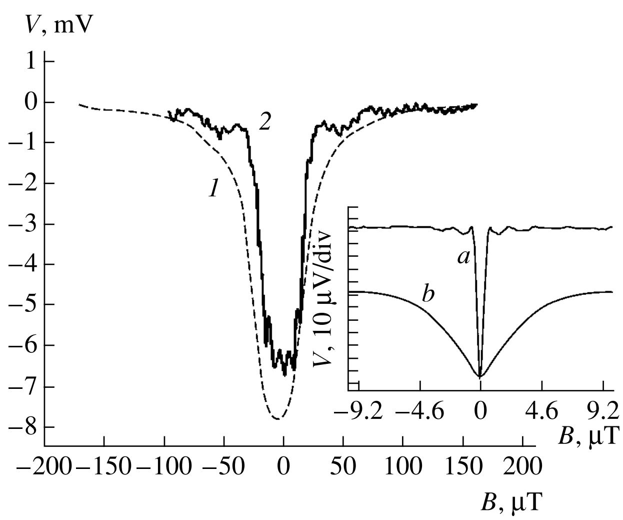

Fig. 2. The typical $V(B)$ curves for (*1*) a serial SQIF consisting of 20 SQUIDs and (*2*) a chain of 20 identical SQUIDs. The inset shows the results of $V(B)$ calculations for a SQIF with N = 30 and a normalized inductance of l = 0 (*a*) and 1.4 (*b*) [8].

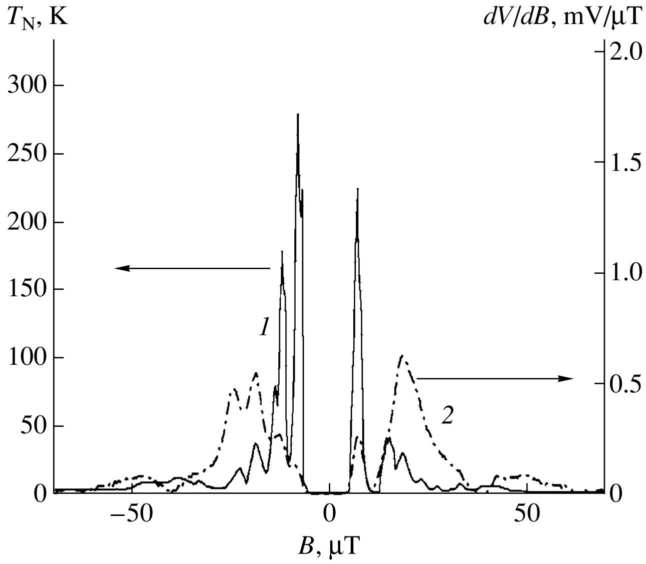

Fig. 3. Experiential plots of (*1*) the equivalent noise power temperature T_N measured in the frequency band f = 1–2 GHz and (*2*) the $V(B)$ curve slope $\partial V/\partial B$ versus magnetic field for a SQIF based on bicrystal neodymium gallate substrate.

the regular chains exhibit both types of $V(B)$ modulation, which is related to the $I_C(B)$ dependence caused by the magnetic field penetration into the Josephson junction. Figure 2 shows that the interference of $V_i(B)$ responses of individual SQUIDs with various loop areas in the SQIF leads to the suppression of side maxima and the smoothing of the main peak envelope.

As expected, the range of voltage V variation for a single SQUID is much smaller than that for the chain. An increase in the central peak $V(B)$ for the regular chain and the SQIF as compared to a single SQUID is explained by the addition of voltage drops on individual loops and is determined by the sum of the corresponding characteristic voltages V_{0i}. However, the peak height V_S = 8 mV observed for the SQIF is smaller than the anticipated sum ΣV_{0i} = 20 mV. Numerical calculations showed that $V(B)$ is strongly influenced by the spread of parameters and the relatively large values of the normalized inductance ($l = L/L_J > 1$, where L is the SQUID loop inductance determined by its geometry and $L_J = \Phi_0/2\pi I_C$ is Josephson's inductance). Using the magnetic-field dependence of the critical current $I_C(B)$ for a single SQUID, the inductance of a loop with S = 35 μm² was estimated as $L = 15 \pm 5$ pH, and the relative critical current spread as $\Delta I/\bar{I}_C$ = 30 ± 10%. Assuming a 50% spread of the critical currents I_{Ci} of Josephson junctions in the SQUID chain and taking l = 4–6 pH (which is close to the available experimental data), a decrease in the central $V(B)$ peak height for the SQIF can be estimated as approximately threefold. At the same time, the range of $\partial V/\partial B$ linearity (determining the working region of the $V(B)$ characteristic) for the SQIF has proven to be ten times greater than for the regular SQUID chain and amounted to 5 mV. According to calculations [8–10], the $V(B)$ peak width in the SQIF is determined by the average loop area and increases with the inductance of the maximum loop (see the inset in Fig. 2). In our SQIF, the $V(B)$ peak width corresponded to an effective junction area of S_{eff} = 30 μm², as determined for the first minimum of the $V(B)$ characteristic of a single SQUID and a SQUID chain defined as $B_1 = \Phi_0/S_{eff}$, where $\Phi_0 = h/2e$ is the flux quantum. An important characteristic (independent of the loop area) is offered by the coefficient of the magnetic-flux-to-voltage conversion, which is defined as $\partial V/\partial\Phi = \partial V/\partial B \cdot \partial B/\partial\Phi$. Determining $\partial V/\partial\Phi$ at the first maximum of the $V(B)$ curve and using the experimental slope $\partial V/\partial B$ = 270 V/T, we obtain $\partial V/\partial\Phi = 40$ mV/Φ_0, which is significantly greater than the value $\partial V/\partial\Phi = 1$ mV/Φ_0 for a single SQUID [13].

Figure 3 shows the magnetic-field dependences of (*1*) the equivalent noise power temperature $T_N(B)$ and (*2*) the $V(B)$ curve slope $\partial V/\partial B$ measured at the SQIF output in the frequency band f = 1–2 GHz at a temperature of 4.2 K and a fixed bias current of $I = 1.25I_C$. As can be seen, the peaks of $T_N(B)$ are observed for the same fields as the peaks of $\partial V/\partial B$. The ratio of the power levels for the maximum T_N peak to the background noise temperature for the measuring system was 15 dB. The appearance of a broadband T_N noise signal for the SQIF can be related to a superposition of thermal voltage fluctuations with a spectral density of $S_V = \Sigma(8kTR_{di}^2/R_{Ni})[1 + 1/2(I/I_C)^2]$ (where R_{di} is the differential resistance of the Josephson junction) and the voltage-to-flux conversion noise $S_\Phi = \Sigma(2kTL_i^2/R_{Ni})(\partial V_i/\partial\Phi_i)^2$. For the SQIF, the experimental values of I/I_C = 1.25 and R_d = 30 Ω obtained for the $T_N(B)$ peak lead to the relation $S_\Phi \gg S_V$, which indicates that the observed noise is mostly due to the process of voltage-to-flux conversion $(\Sigma L_i\partial V_i/\partial B_i^*)^2$. It should be noted that an additional mechanism responsible for the appearance of a noiselike signal at the SQIF output can be related to mixing of the intrinsic Josephson generation frequencies (with relatively large widths Δf_j on the order of several gigahertz) for individual Josephson junctions possessing nonidentical bias voltages (due to a scatter of the R_{Ni} values). In order to estimate the possible value (T_{mix}) of this noise, we have studied the process of frequency conversion on the SQIF in the 4- and 6-mm wavelength intervals. In these experiments, a monochromatic signal (with a linewidth on the order of 100 kHz) from a Gunn oscillator was applied to the SQIF input and the minimum input power P_e of this signal was determined that was sufficient to detect a converted signal response under the experimental conditions analogous to those used in the $T_N(B)$ measurements. The results of these experiments showed that, to obtain a response comparable with the background T_N level (the region of $B > 50$ mT in Fig. 3), the P_e value must be 40 dB greater than the intrinsic Josephson's generation power for the individual Josephson junctions in the SQIF. Taking into account the ratio of the generation linewidth of the SQIF Josephson junction and the measuring oscillator, we obtained an estimate of $T_{mix} < 10$ K, which is significantly lower than the T_N peak height.

In conclusion, we have fabricated and studied the SQIF structures based on an oxide superconductor bicrystal, which can be used in the microwave frequency range. The SQIF operation was studied in a regime where the voltage–flux (V–Φ) characteristic is determined by the magnetic-field dependence of the critical current $I(B)$ in an individual Josephson junction. The slope of the V–Φ curve measured for the SQIF is at least one order of magnitude greater than the values reported for the known SQUIDs. The output noise level is correlated with the slope of the V–Φ curve. The scatter of SQIF parameters observed in experiments decreases the (V–Φ) conversion coefficient, which can be increased by reducing the SQUID array size and, hence, the loop inductance.

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